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# The association between greenness exposure and COVID-19 incidence in South Korea: An ecological study

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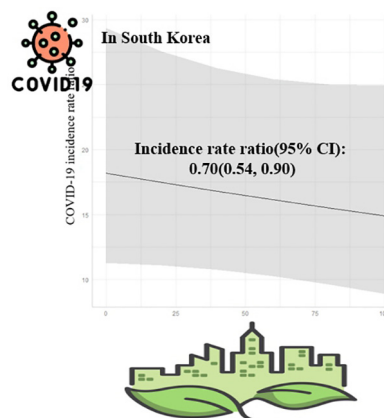
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## HIGHLIGHTS

- We aimed to elucidate the association between greenness exposure and COVID-19 cases.
- South Korean district-level data covering a year of COVID-19 cases were analyzed.
- Higher natural greenness exposure rates were associated with lower COVID-19 incidence rate.
- COVID-19 cases were associated with demographic, socioeconomic, and health statuses.

## GRAPHICAL ABSTRACT



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## ABSTRACT

**Background:** The rapid spread of COVID-19 has caused an emergency situation worldwide. Investigating the association between environmental characteristics and COVID-19 incidence can be of the occurrence and transmission. The objective of this study was to evaluate the association between greenness exposure and COVID-19 cases at the district levels in South Korea. We also explored this association by considering several environmental indicators.

**Methods:** District-level data from across South Korea were used to model the cumulative count of COVID-19 cases per 100,000 persons between January 20, 2020, and February 25, 2021. Greenness exposure data were derived from the Environmental Geographic Information Service of the Korean Ministry of Environment. A negative binomial mixed model evaluated the association between greenness exposure and COVID-19 incidence rate at the district level. Furthermore, we assessed this association between demographic, socioeconomic, environmental statuses, and COVID-19 incidence.

**Results:** Data from 239 of 250 districts (95.6%) were included in the analyses, resulting in 127.89 COVID-19 cases per 100,000 persons between January 20, 2020 and February 25, 2021. Several demographic and socioeconomic variables, districts with a higher rate of natural greenness exposure, were significantly associated with lower COVID-19 incidence rates (incidence rate ratio (IRR), 0.70; 95% confidence interval (CI), 0.54–0.90;  $P$ -value = 0.008) after

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adjusting covariates, but no evidence for the association between built greenness and COVID-19 incidence rates was found.

**Conclusion:** In this ecological study of South Korea, we found that higher rates of exposure to natural greenness were associated with lower rates of COVID-19 cases.

## 1. Introduction

The rapid spread of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has caused an emergency situation worldwide (Sohrabi et al., 2020). SARS-CoV-2 is a highly pathogenic and transmissible virus which causes coronavirus disease 2019 (COVID-19) (Russette et al., 2021). Since vaccines were not available until the end of 2020 and due to the scarcity of effective treatments, population-level public health measures were put in place to control the outbreak, including social distancing, stay-at-home orders, nationwide lockdowns, and public education initiatives (Alfano and Ercolano, 2020; Tammes, 2020).

In South Korea, the first patient was diagnosed on January 20, 2020. On May 2, a total of 10,799 people were diagnosed with COVID-19. The fatality rate was 2.4%, which translates to 4.94 fatalities per million (Park et al., 2020c). During the COVID-19 pandemic in South Korea, public health authorities conducted rapid and strict contact tracing, isolation of confirmed cases, and quarantined the suspected COVID-19 cases (Park et al., 2020a). The government implemented strict nationwide social distancing guidelines, however, school shutdowns and strict closures were not implemented (Shim et al., 2021). South Korea experienced three waves of the COVID-19 until December 2020. The first wave from February until March was related to religious group gatherings in the local area. The daily new cases in the second wave, comprising 441 cases on August 26, were related to worship services in the densely populated Seoul areas. The third wave in December 2020, however, had more than 1000 daily new cases. The third wave also had a fatality rate higher than that in the second wave (1.26% vs. 0.91%) (Seong et al., 2021).

Regarding non-pharmaceutical interventions (NPI) to contain the spread of COVID-19, South Korea is one of the few countries that had not implemented restrictions such as large-scale lockdowns or stay-at-home orders (Dighe et al., 2020; Jeong et al., 2020; Yoo et al., 2021). Instead of stringent NPI, the South Korean government focused on an aggressive “test, trace, isolate” strategy (Dighe et al., 2020). Although social distancing measures were introduced in areas with high incidence rates, these measures were applied for a relatively short period as the number of cases decreased. Social distancing measures are divided into three stages, and containment was required at the highest stage, but this was not implemented. In addition, there was relatively little difference between regions (Yoo et al., 2021). During the pandemic, individuals adopted safety measures such as wearing masks, prioritizing handwashing, good personal hygiene, practicing respiratory cough etiquette, as well as avoiding crowds, not using public transportation, and maintaining at least 6 f. distance from others. A recent epidemiological study showed that outdoor physical activities increased during the pandemic compared to time before the implementation of social distancing policy (Park et al., 2020b). The study also suggested if physical distancing measures are maintained carefully during the pandemic, outdoor physical activity can be safe for people and the spread of infection can be stabilized (Park et al., 2020b).

Environmental characteristics are indivisibly linked with the occurrence and spread of diseases (Jian et al., 2014). Previous studies have shown that several environmental factors, including air pollution (Wu et al., 2020a), greenness exposure (Klompaker et al., 2021; Russette et al., 2021), temperature (Shi et al., 2020), and humidity (Wang et al., 2020), were associated with the spread, transmission, and reduction of COVID-19 due to the stability of the virus as well as host susceptibility. Spotswood et al. suggested that nature plays an important role in building defenses against viruses through boosting natural killer cells. Their result showed that an increase of 0.1 in the Normalized Difference Vegetation

Index was associated with a 4.1% decrease in COVID-19 incidence rate (Spotswood et al., 2021).

A recent emerging and growing body of data has led many to suggest that greenness exposure could benefit health outcomes of various diseases including infectious diseases (Cunha et al., 2021; Eldeirawi et al., 2019; Ferrante et al., 2020; Huang et al., 2018; Squillacioti et al., 2020; Sun et al., 2020). Links between greenness and health elaborating the potential pathways was noted which included harm reduction and restoring and building capacities (Markevych et al., 2017). The mediating factors of this association were also reported to include reduced stress (McCormick, 2017), increased physical activity (Marquet et al., 2020), filtered out air pollution (Nowak et al., 2006), decreased traffic-related noise (Dzhambov et al., 2019), and enhanced social interaction (Liu et al., 2019). Several studies have provided the importance of public green spaces because exposure to more green during COVID-19 seemed to reduce air pollutants and increased time in nature has been linked to positive behavioral changes (Diener and Mudu, 2021; Labib et al., 2021). Scientific evidence supports the beneficial role of environmental factors such as greenness and biodiversity in regulating the human immune system (Copat et al., 2020; Marselle et al., 2021; Rook, 2013), however, only a few studies have considered greenness exposure in relation to COVID-19 incidence rate. Four US studies suggested that counties with higher exposure to greenness had better COVID-19 outcome measures, including incidence and mortality rates (Klompaker et al., 2021; Lee et al., 2021c; Russette et al., 2021; Spotswood et al., 2021). However, the impact of local environmental conditions on the spread of the virus should be further investigated in Asian countries. Moreover, it is still unclear whether greenness exposure and the incidence of COVID-19 cases are related and to what extent socio-demographic factors, such as age and socioeconomic status, play a role in explaining the number of COVID-19 cases in the previous studies. Therefore, this study aimed to evaluate the association between greenness exposure and COVID-19 cases across 239 districts in South Korea using an ecological study design. We also explored this association by considering several environmental indicators.

## 2. Material and methods

### 2.1. Study design

South Korea is composed of 250 districts, the basic administrative units of Korea, in eight metropolitan cities and nine provinces. We excluded from analysis eight districts near the border with North Korea for which greenness exposure data were not available due to security reasons, one district in Daegu city as its outbreak pattern differed from that of other places because of its association with a religious institute, and two districts due to the lack of exact information on COVID-19 cases. Finally, we included 239 districts in this study.

### 2.2. Variables

#### 2.2.1. COVID-19 data

We obtained COVID-19 counts for the included South Korean districts from the Central Disaster Management Headquarters (<http://ncov.mohw.go.kr/en/>). This source provides the most comprehensive district-level COVID-19 data to date and is updated daily by the Korean government. We collected the cumulative number of confirmed cases for each district up to February 25, 2021, the period before vaccinations started in South Korea. District-level COVID-19 incidence rates were defined for this analysis as the number of COVID-19 cases per 100,000 persons in the district.

### 2.2.2. Greenness

For each district, greenness exposure was estimated using Landsat image data from the SPOT-5 satellite images collected by the Environmental Geographic Information Service, Ministry of the Environment. We used 1:25,000 maps at 5 m per pixel space resolution with 814 sheets (Choi et al., 2015). We downloaded the Landsat image data with a shapefile, then we combined it to the administrative district map from the open data (<http://www.gisdeveloper.co.kr/>) using a geometric intersection tool of the ArcGIS desktop version 10.5 software (ESRI Inc., Redlands, CA, USA). We calculated the ratio of the quotient of green area divided by total area (square meter divided by square meter). We separately analyzed two types of greenness: natural greenness, which included forests and natural grasslands, and built greenness, which included golf courses, cemeteries, artificial grassland, and street trees. The definition of each type of greenness was presented in table S1 (Lee et al., 2021b).

### 2.2.3. Covariates

Based on previous studies and considering the goodness of fit test in the model, we selected ten potential confounding factors for each district that included demographic, socioeconomic, environmental, comorbid or behavioral variables (Klompaker et al., 2021; Lee et al., 2021c; Russette et al., 2021).

We obtained from Statistics Korea (<http://kostat.go.kr/portal/eng/index.action>) information on the percentage of older people (aged 65 years and older) in the population, and this is a demographic variable. We also obtained data on four socioeconomic variables, house prices (median apartment price), percentage of people educated to the high school level or above in the adult population (aged  $\geq 20$  years), deprivation index (range, 0–500), and the proportion of apartments residents. The data on house prices were collected from the Ministry of Land, Infrastructure and Transport and those on the education level from Statistics Korea. The deprivation index was calculated as the sum of the scores of five domains, including unemployment, poverty, housing, labor, and social networks. Higher deprivation index score indicated greater deprivation (Shin et al., 2009). Since COVID-19 spreads quickly through close contact in an enclosed space, we included the proportion of apartment residents per administrative unit as a covariate.

The district-level environmental variables included NO<sub>2</sub> concentration and temperature based on previous studies about the relationship between exposure to air pollution, temperature, district-level information on the number of urbanity, and the number of confirmed cases less than 10 (Klompaker et al., 2021; Raines et al., 2021; Wu et al., 2020b). The NO<sub>2</sub> concentration was computed by annual average concentration in 2019 from the mean hourly data from the Air Korea website (<http://www.airkorea.or.kr/eng/>). The hourly NO<sub>2</sub> for the 364 Air Korea monitoring stations were measured using the chemiluminescent methods, which provide the data regarding the outdoor air quality and is managed by the Korean Ministry of Environment (Lee et al., 2021a). Because the monitoring stations were not covered for all districts, we estimated that through kriging interpolation for each district (Lee et al., 2020a; Oliver and Webster, 1990). We also computed the average summer (June–August) and winter (December–February) temperatures from the hourly ambient temperature data in 2019, which was obtained from the Meteorological Administration. To show the different transmission dynamics between urban and rural areas, as well as a proxy for the stage of the COVID-19 outbreak, we included a dummy variable for urban areas (i.e., eight metropolitan cities) or rural areas (i.e., nine provinces), and a dummy variable for a district with confirmed cases less than 10 (Yes) or 10 cases and more (No).

District-level comorbid or behavioral variables in the adult population included the percentages of people with diabetes mellitus, hypertension, and moderate physical activity. We collected these district-level variables from the Community Health Survey (Kang et al., 2015). Detailed information on how these data were collected is described in table S2. We tested a variance inflation factor (VIF) as a diagnostic tool for multi-collinearity to assess whether the covariates were inflated when the VIF was large (VIF >10) (Table S3) (Tu et al., 2005). We also displayed a cross-

correlation to estimate how the variables correlated with each other (Fig. S1).

### 2.3. Statistical analysis

The ArcGIS desktop version 10.5. software (ESRI Inc., Redlands, CA, USA) was used to visualize the spatial distribution of greenness exposure and COVID-19 incidence rate ratio (IRR) across South Korea. We examined the descriptive statistics of the 239 districts. We estimated the significance of the association between greenness and covariates, and the association between covariates and COVID-19 IRR to select the modifier or pure confounder (Blakely and Woodward, 2000). We also examined the association between greenness and covariates using Pearson's correlation analysis for continuous covariates, and Student's *t*-test for categorical covariates (Table S4). We estimated the association between the covariates and COVID-19 IRR in univariate models on COVID-19 IRR. Subsequently, we used a negative binomial generalized linear mixed model, with districts as random intercepts and a population size (log transformed) as offset variable, to account for the overdispersion of the data, we performed model fitting to estimate the linearity for the association of greenness with COVID-19 IRR using the *glmmTMB* function in R package (Magnusson et al., 2017). We also plotted the relationship of greenness with each covariate to test this linearity (Fig. S2). For the main model, the associations of greenness exposure per interquartile range (IQR) increase were expressed in terms of the increase in COVID-19 incidence rate using the crude, multivariate models adjusting for pure confounders and multivariate models adjusting for the overall covariates. These analyses were conducted using a negative binomial mixed model, with population size offset and random intercept by districts, to account for potential correlation between districts within the same local area for estimating the association between exposure to greenness and COVID-19 IRR; the 95% confidence interval (CI) per IQR greenness increase was determined using PROC GLIMMIX in SAS (version 9.4; SAS Institute, Cary, NC, USA). Compound symmetry was assumed for the covariance structure, considering the spatial proximity of residents in each district in previous studies (Lee et al., 2009; Lee et al., 2019a; Lee et al., 2020a; Lee et al., 2019b). In sensitivity analyses, we conducted the association between greenness and COVID-19 IRR by stratifying into quantiles of the population density, and deprivation index to estimate whether there were different effects depending on these variables as a moderator.

## 3. Results

### 3.1. The pandemic status in South Korea

The first case of COVID-19 in South Korea was reported on January 20, 2020. As of February 25, 2021, the day before vaccination against COVID-19 started in the country, 88,922 confirmed cases of COVID-19 were reported in South Korea. Table 1 shows the mean COVID-19 incidence rates in eight cities and nine provinces in South Korea until February 25, 2021. Seoul City, Daegu City, and Jeju Province had the highest mean incidence rates, reaching 264, 303, and 297 cases per 100,000 persons, respectively.

### 3.2. Descriptive statistics of the 239 districts

Our study included 239 out of 250 districts of South Korea. The highest percentages of greenness were seen in districts along the east coast and the southern areas (Fig. 1). At the district level, the top three highest COVID-19 incidence rates were seen in Cheorwon-gun, Sunchang-gun, and Cheongdo-gun (Fig. 2). On the other hand, the highest percentages of built greenness were seen in districts with metropolitan cities. The mean percentage  $\pm$  standard deviation (SD) of adults older than 64 years and adults educated to the high school level or above were  $19.89 \pm 8.23\%$  and  $66.55 \pm 14.39\%$ , respectively. The mean natural, and built greenness percentages in all 239 districts were 46.99%, and 2.21%, respectively. The mean



**Table 1**

Cumulative incidence of COVID-19 cases in the 17 Korean cities and provinces until February 25, 2021.

Cities/provinces	Numbers of districts	Population	Mean COVID-19 Cumulative incidence
Metropolitan cities(urban area)			
Seoul	25	9,578,975	264.89
Busan	16	3,390,160	78.84
Daegu	7	2,284,188	303.09
Incheon	10	2,927,320	129.28
Gwangju	5	1,448,843	123.94
Daejeon	5	1,471,770	114.26
Ulsan	5	1,145,705	89.91
Sejong	1	326,245	67.13
Provinces(rural area)			
Gyeonggi	37	12,097,550	176.54
Gangwon	15	1,397,233	131.67
Chungbuk	14	1,589,355	65.97
Chungnam	16	2,110,584	103.46
Jeonbuk	13	1,166,376	71.72
Jeonam	22	1,863,279	37.51
Gyeongbuk	24	2,653,916	118.75
Gyeongnam	22	3,348,258	57.81
Jeju	2	663,489	296.93
Total	239	49,463,241	127.89

Note: mean cumulative incidence was calculated by cases by population per each city or province per 100,000 persons.

COVID-19 incidence was 127.9 cases per 100,000 persons, calculated for the period from January 20, 2020, to February 25, 2021 (Table 2).

### 3.3. Association between greenness and COVID-19 IRR

The explored associations between various covariates and COVID-19 IRR are presented in Table 3. In the univariate models, districts with higher house prices (IRR, 1.69; 95% CI, 1.46–1.96), a higher proportion of apartments (IRR, 1.00; 95% CI, 1.00–1.01), districts with urbanity (IRR, 1.65;

95% CI, 1.32–2.06 compared to the rural area), a higher percentage of adults educated to the high school level or above (IRR, 1.02; 95% CI, 1.01–1.02), higher deprivation index (IRR, 1.32; 95% CI, 1.09–1.60), and higher annual NO<sub>2</sub> concentrations (IRR, 1.04; 95% CI, 1.03–1.05), a higher average temperature for the summer season (IRR, 1.16; 95% CI, 1.03–1.31) had a significantly higher risk of high COVID-19 IRR, while districts with a higher prevalence of people aged 65 years (IRR, 0.96; 95% CI, 0.95–0.98), with a lower average temperature for the winter season (IRR, 0.91; 95% CI, 0.86–0.95) had a significantly lower risk. The overall exposure-response curve for COVID-19 incidence showed a linear negative relationship with natural greenness but a positive relationship with built greenness, after adjusting for covariates using a negative binomial mixed model (Fig. 3). In the multivariate model adjusting for pure confounders, we found no association between natural or built greenness, and COVID-19 IRR. However, in the full models, we found IRRs of 0.70 (95% CI, 0.54–0.90) when one-IQR natural greenness increased. These associations between built greenness and COVID-19 still remained no significant even after further adjustment for overall covariates in the full model (IRR, 1.00; 95% CI, 0.88–1.14) (Table 4). In subgroup analysis, we found that there are no statistically significant associations between greenness and COVID-19 incidence by stratifying into the quantiles of population density, and deprivation index, and we also did not find any significant interaction effects by these strata in Table S5.

### 4. Discussion

We found that greenness was significantly associated with the COVID-19 IRR. Interestingly, an IQR increase in natural greenness was associated with a COVID-19 IRR decrease after adjusting for potential district-level confounders. We also found that South Korean districts with higher house prices, higher annual NO<sub>2</sub> concentrations, higher deprivation index, higher proportion of apartments, greater urbanization, higher average temperature during the summer season, lower average temperature during winter season, higher rates of people with high school education or above, lower

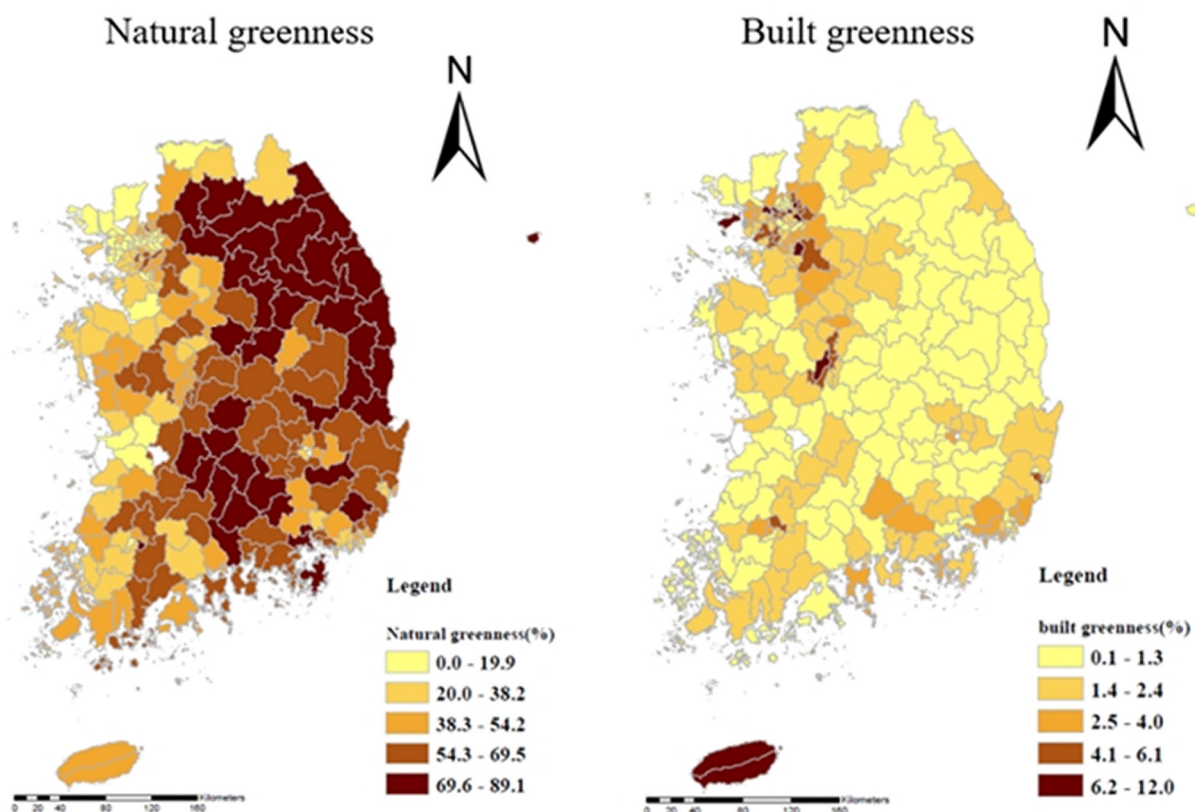


Fig. 1. Spatial distribution of greenness in South Korea, measured from Landsat image data.

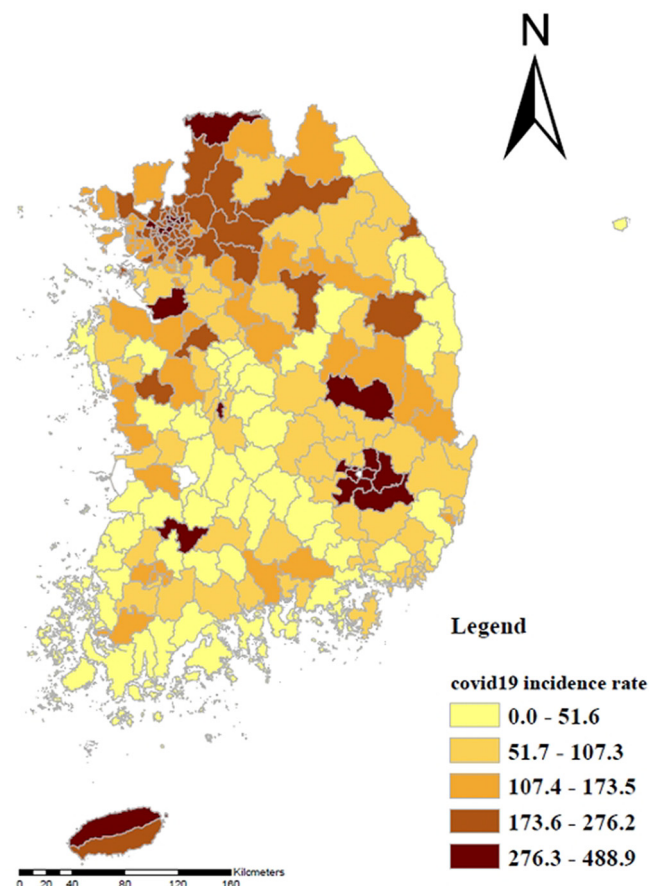


Fig. 2. Map of the COVID-19 incidence rate ratios in 239 districts in South Korea. Abbreviations: COVID-19, coronavirus 2019.

population of the elderly, were at a higher risk of having a high COVID-19 IRR.

Understanding the relationship that environmental and socioeconomic factors have with infectious diseases could lead to better disease prevention strategies (Huang et al., 2018); however, few studies previously have reported on the impact of greenness on infectious diseases including COVID-19. Huang et al. reported the association between greenness and a dengue fever (DF) outbreak in Taiwan using a spatial autocorrelation method and generalized linear mixed models (Huang et al., 2018). They suggested a high aggregation of DF hotspots in the metropolitan areas of

Taiwan, a positive correlation between parks and DF, and a negative association between other land types and DF. However, a study in South America reported that there was no significant association between greenness and DF. This study suggested that socioeconomic vulnerability was a strong modifiable confounder for this association (Cunha et al., 2021). Recently, four US ecological studies have shown an association between greenness exposure and low COVID-19 mortality and incidence rates (Klompaker et al., 2021; Lee et al., 2021c; Russette et al., 2021; Spotswood et al., 2021). Russette et al. found that the top three greenspace deciles were significantly associated with a reduced risk of COVID-19 mortality (Russette et al., 2021). They suggested that counties with a higher prevalence of health coverage for very low-income earners (Medicaid) had a significantly lower risk of COVID-19 mortality. Klompaker et al. reported stronger associations between greenness and COVID-19 incidence than mortality (Klompaker et al., 2021), possibly because greenness affected contact rates during the COVID-19 pandemic. COVID-19 mortality was related to treatments and host susceptibility due to factors such as age and the presence of chronic diseases (Klompaker et al., 2021). Lee et al. showed that population density was associated with worse COVID-19 outcomes, including transmission and mortality (Lee et al., 2021c); thus, areas with higher greenness had lower COVID-19 incidence, transmission, and mortality rates. They also suggested that higher greenness was strongly associated with lower population density and that this provided many opportunities for outdoor activities, resulting in a lower transmission risk than being involved in indoor activities (Lee et al., 2021c).

Several studies reported that people spent significantly more time in greenness and visited nature more often during the pandemic than before (Robinson et al., 2021; Soga et al., 2021; Venter et al., 2020). The study by Robinson et al. estimated the individual mental well-being index using a digital questionnaire and well-being instruments. They suggested that increased greenness surrounding a participant's residence was associated with better mental well-being during the COVID-19 pandemic (Robinson et al., 2021). In line with this study, several previous studies showed that greenness was beneficial to mental and physical health outcomes, such as mental well-being scale and self-reported general health, during the COVID-19 pandemic (Slater et al., 2020; Ugolini et al., 2020). Potential mechanisms for this association could be that neighborhoods with higher greenness could affect the host susceptibility (Klompaker et al., 2021), lower the rates of person-to-person contact (Klompaker et al., 2021), improved the air quality (Diener and Mudu, 2021; Ji et al., 2020), and present a wide diversity of microorganisms that could regulate the human immune system (Roslund et al., 2020). However, further studies should investigate the role of biological mechanisms in the association between greenness exposure and infectious diseases. We found that the districts with higher natural greenness were associated with a lower COVID-19 incidence rate in South Korea, whereas, higher built greenness had no association with

Table 2  
Characteristics of the 239 districts.

Variable	Sub-variable	Median	Mean	SD	Min	Max	IQR
Outcome	COVID-19 incidence per 100,000 persons per districts (%)	99.76	127.89	98.97	0.00	488.89	–
Explanatory	Natural greenness (%)	48.48	46.99	22.49	0.00	89.11	33.37
	Built greenness (%)	1.66	2.21	2.07	0.06	12.04	1.72
Covariates							
Demographic status	Aged ≥ 65 years (%)	17.46	19.89	8.23	6.58	39.49	–
Socioeconomic status	House price(log-transformed)	15.68	15.85	0.64	14.73	17.72	–
	Adults with high school education (%)	69.31	66.55	14.39	36.54	99.58	–
	Deprivation index(log-transformed)	4.55	4.54	0.52	2.82	5.79	–
	The proportion of apartments residents(%)	55.96	49.29	25.03	0.12	93.05	–
Environmental status	Annual NO <sub>2</sub> concentration (ppb)	17.03	17.57	7.37	4.17	33.14	–
	Average summer temperature(June–August)	24.27	24.24	0.73	21.78	25.52	–
	Average winter temperature(December–February)	1.52	1.97	2.00	–2.36	8.81	–
	Districts with urbanity, n(%)	74 (30.9)					
Comorbid or behavioral status	Districts with confirmed cases less than 10, n(%)	22 (9.21)					
	Adults with diabetes mellitus (%)	8.00	8.05	1.31	5.00	11.80	–
	Adults with hypertension (%)	19.30	19.41	2.25	14.90	27.40	–
	Adults with moderate physical activity (%)	24.80	25.36	6.89	5.50	56.90	–

Abbreviations: COVID-19, coronavirus 2019; SD, standard deviation; IQR, interquartile range.

**Table 3**  
Associations between covariates and COVID-19 incidence rate in univariate models.

Variable	Sub-variable	COVID-19 incidence	
		IRR (95% CI)	P-value
Demographic status	People aged $\geq 65$ years (%)	<b>0.96(0.95, 0.98)</b>	<b>&lt;0.0001</b>
Socioeconomic status	House price(log-transformed)	<b>1.69(1.46, 1.96)</b>	<b>&lt;0.0001</b>
	Adults with high school education status(%)	<b>1.02(1.01, 1.02)</b>	<b>&lt;0.0001</b>
	Deprivation index(log-transformed)	<b>1.32(1.09, 1.60)</b>	<b>0.004</b>
	The proportion of apartments residents(%)	<b>1.00(1.00, 1.01)</b>	<b>0.002</b>
Environmental status	Annual NO <sub>2</sub> concentration (ppb)	<b>1.04(1.03, 1.05)</b>	<b>&lt;0.0001</b>
	Average summer temperature	<b>1.16(1.03, 1.31)</b>	<b>0.012</b>
	Average winter temperature	<b>0.91(0.86, 0.95)</b>	<b>0.000</b>
	Districts with urbanity, yes(reference: no)	<b>1.65(1.32, 2.06)</b>	<b>0.000</b>
Comorbid or behavioral status	Adults with diabetes mellitus (%)	0.97(0.90, 1.04)	0.472
	Adults with hypertension (%)	0.98(0.93, 1.03)	0.552
	Adults with moderate physical activity (%)	0.99(0.97, 1.00)	0.281

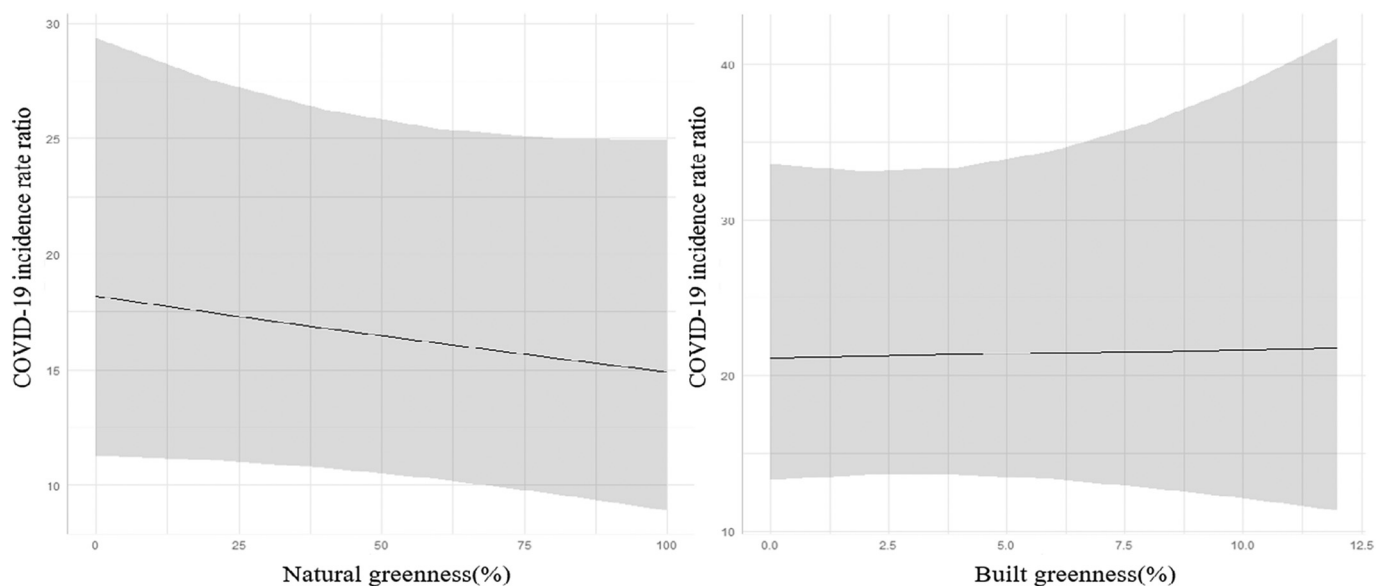
A univariate model conducted using negative binomial mixed model. Statistically significant values are marked in bold ( $P < 0.05$ ). Abbreviations: COVID-19, coronavirus 2019; IRR, incidence rate ratio; CI, confidence interval.

COVID-19 incidence rate. The result showed that districts with higher urbanization such as higher population, a high proportion of apartment residents, and high percentages of people aged at least 65 years had a lower rate of natural greenness. However, after adjusting for these covariates, there was a significant association noted between natural greenness and COVID-19 IRR. It suggested the probability that natural and built greenness has different effects on health outcomes. However, only a few previous studies have considered the differences between types of greenness. Thus, more research using the type of greenness as an indicator should be conducted in the future.

Our univariate model results suggested that districts with higher house prices, higher rates of people with high school education or above, higher annual NO<sub>2</sub> concentrations, and lower rates of older people were associated with an increased risk of COVID-19 incidence. Consistent with previous studies, people living in these environments usually have a more active social life and, therefore, have higher COVID-19 transmission and incidence rates (Boehmer et al., 2020; Lee et al., 2020b). Our finding of districts with high deprivation index was also consistent with the results of previous studies. These people may have been at a higher risk due to poor health (Lee et al., 2021c) and prohibitions from working at home (Control and

Prevention, 2020). We found that many of the observed effects related to urbanization include urbanity, population density, the percentages of people aged 65 and over, house prices, the percentage of residents in apartments. In previous studies, urbanization has been associated with an increased risk of infection (Eliyahu and Boaz, 2020). However, the chances of mortality are reduced due to effective medical services compared to rural areas (Eliyahu and Magid, 2021). Moreover, the screening rate of COVID-19 infection was related to urbanity, still, further attention is required to consider the developed indicator of urbanity along with the association between greenness and COVID-19 infection. We found that a significantly negative association between natural greenness and COVID-19 IRR was observed, but no evidence for the association built greenness and COVID-19 IRR.

This study had some limitations. First, we used aggregated data that did not infer causality and may have caused the “ecological fallacy” such that factors correlated with the study outcomes using grouped data might be uncorrelated with the individual-level data (Greenland, 1994). Second, this study could not determine whether higher rates of surrounding greenness mean higher accessibility to greenness during the pandemic in South Korea. Third, we may have missed the adjustment for potential



**Fig. 3.** The association between greenness and COVID-19 incidence rate among 239 districts. Abbreviations: COVID-19, coronavirus 2019. Models included a population size (log transformed) offset and a random intercept by district and adjusted for percentage of people aged  $\geq 65$  years, house price (log transformed), deprivation index (log transformed), annual NO<sub>2</sub> concentration, average summer temperature, average winter temperature, the proportion of apartments residents, Districts with urbanity, Districts with confirmed cases less than 10, and percentages of adults with high school education status, adults with diabetes mellitus, adults with hypertension, and adults with moderate physical activity using negative binomial mixed model.



**Table 4**

Associations between greenness exposure and COVID-19 incidence rate ratios.

Greenness	Unadjusted model <sup>1</sup>		Adjusted model1 <sup>2</sup>		Adjusted model2 <sup>3</sup>	
	IRR (95% CI)	P-value	IRR (95% CI)	P-value	IRR (95% CI)	P-value
Natural greenness	<b>0.68(0.59, 0.79)</b>	<b>&lt;0.0001</b>	0.90(0.70, 1.14)	0.400	<b>0.70(0.54, 0.90)</b>	<b>0.008</b>
Built greenness	<b>1.15(1.06, 1.26)</b>	<b>0.001</b>	0.97(0.88, 1.08)	0.689	1.00(0.88, 1.14)	0.918

Note: Statistically significant values are marked in bold ( $P < 0.05$ ).

Abbreviations: COVID-19, coronavirus 2019; IRR, incidence rate ratio; CI, confidence interval.

<sup>1</sup> Unadjusted model was conducted using negative binomial mixed model.<sup>2</sup> Adjusted Model1 included a population size offset and a random intercept by district and adjusted for pure confounders such as percentage of people aged  $\geq 65$  years, house price (log transformed), deprivation index (log transformed), annual NO<sub>2</sub> concentration, average summer temperature, the proportion of apartments residents, Districts with urbanity, Districts with confirmed cases less than 10, and percentages of adults with high school education status, using negative binomial mixed model.<sup>3</sup> Adjusted Model2 included a population size offset and a random intercept by district and adjusted for percentage of people aged  $\geq 65$  years, house price (log transformed), deprivation index (log transformed), annual NO<sub>2</sub> concentration, average summer temperature, average winter temperature, the proportion of apartments residents, Districts with urbanity, Districts with confirmed cases less than 10, and percentages of adults with high school education status, adults with diabetes mellitus, adults with hypertension, and adults with moderate physical activity using negative binomial mixed model.

confounding variables, including several indicators related to viral transmissions such as accessibility of screening centers or level of social distancing measures, and unmeasured for urbanity. However, South Korea's COVID-19 response focused on “test, trace, isolation” strategies rather than large-scale lockdowns or strong social distancing. In fact, the government set up about 600 screening centers nationwide in March 2020, and social distancing measures were carried out nationwide in a relatively short period of time (Yoo et al., 2021). Therefore, these effects will not be perverse to the results. Finally, the acquisition dates for some covariates including the greenness and deprivation index were over 10 years ago because the latest variables with each district were not available. However, this might not be a major concern because the rate of change in forested areas in South Korea is typically modest (<5% changes between 2008 and 2019; Table S6). Despite these limitations, our study has several strengths. First, to our knowledge, this is the first study to examine the association between COVID-19 incidence and greenness in South Korea. Second, we estimated the association between greenness and COVID-19 incidence after adjusting for various potential confounders at the district level. Thus, our results provide scientific evidence for health policy planning, including the allocation of resources, and could guide future health programs for infectious diseases.

## 5. Conclusions

We found that higher exposure to natural greenness was associated with lower rates of COVID-19 cases in South Korea. The exposure to natural greenness may be beneficial for district-level COVID-19 incidence rates in districts with low population density and high NO<sub>2</sub> concentration. Our results provide further evidence of the health benefits of natural greenness in support of public health and improved design of healthy cities during COVID-19 and future pandemics.

## CRedit authorship contribution statement

**KSL:** Conceptualization, formal analysis, and manuscript writing. **HSM, JHY, YJC, and JHB:** Investigation, Writing - review & editing. **HKS:** Data curation, Writing - review & editing, Supervision.

## Ethical approval

For this article, the ethical approval was not required.

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## Declaration of competing interest

The authors have no conflicts of interest to declare for this study.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2022.154981>.

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